DEVELOPING PULSE WIDTH MODULATED POWER SUPPLY FOR THE GeV LIGHT SOURCE

by

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Dated: August 1, 1986

Argonne, IL

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SUMMARY

The magnets for the storage ring of synchrotron 6 GeV light source require power controllers to maintain the magnet currents constant at a predetermined level. Both bidirectional and unidirectional current controls are also required. A low magnet current ripple, typically 0.001 % at a frequency of 20 kHz limits the choice of the power controllers. The number of magnets and the varities of current control requirements add to the design complexity. This report investigates the possible power electronics circuit topologies. New circuit topologies are proposed. The control characteristics of unidirectional transistorized chopper controller are evaluated by using computer-aided models. The areas of further investigations are identified.

Acknowledgement

This work was supported by the Division of Educational Programs at Argonne National Laboratory. Thanks are due to W. F. Praeg for his valuable comments and to Donald G. McGhee and Martin J. Knott for their assistance and suggestions.

$C_{\text{[illegible]}}$ load filter capacitance, F

C_m commutation capacitance, F

$i(t)$ instantaneous resonant current, A

L magnet inductance, H

$L_{\text{[illegible]}}$ load filter inductance, H

L_1 leakage inductance of transformer referred to the primary, H

L_m commutation inductance, H

V_c voltage of the commutation capacitor, V

$V_{\text{[illegible]}}$ voltage of the load filter capacitor, V

$V_{\text{[illegible]}}$ dc input voltage, V

$v_o(t)$ instantaneous dc magnet voltage, V

1. INTRODUCTION

The magnets for the storage ring of synchrotron GeV light source require power controllers to maintain the magnet currents constant at a predetermined level. There are six types of magnets and their voltage and current (and power) requirements for each type are different.

Table 1 shows the specifications for the magnets. The current control requirement is very tight with a ripple current of typically 0.001 %. Apart from the various power requirements, the current control requirement can be divided into two types : (a) unidirectional current control (or one-quadrant operation) and (b) bidirectional current control (two-quadrant operation).

The current control is normally accomplished by adding a static power converter in between the magnet and a fixed dc voltage source. The power converter could be made of power transistors or thyristors or gate turn-off thyristors (GTOs). GTOs require complex gate drive circuitry and would not be suitable for magnets control. However, due to high current requirements for some magnets, the applications of transistors are limited to low power magnets. Thyristors are suitable for high power magnets.

There are large number of magnets and if all the power controllers draw power from the dc source at the same instant of time, the dc voltage level would fall due to its finite regulation and it would be necessary to phase shift the controllers from each other. The operation of power converters requires a low impedance source and an input filter is normally provided for this purpose.

2. ONE-QUADRANT POWER CONTROLLERS

One-quadrant power converter can be implemented by using power transistors or thyristors. The transistorized controller is normally a dc-dc conveter (or chopper). The thyristorized controller can be implememted in two conversion stages: dc-ac-dc using a resonant power converter and rectifier.

2.1 Chopper Controller

The basic arrangement of a transistorized chopper controller is shown in Fig. 1. When transistor Q_1 is turned on, power is transferred to the magnet and when Q_2 is turned off, the magnet current continues to flow though the fee-wheeling diode D_1. The power flow is controlled by varying the on-time of transistor Q_1.

Computer Programs in Advanced BASIC are developed to investigate the control characteristics of a chopper controller. The programs are listed in the Appendix. Fig. 2 shows the variations of chopping frequency against dc input voltage for various current ripple constraints. At a low ripple current, the operating frequency is very sensitive to a change in dc input voltage. The desirable operating frequency should be above 20 kHz to reduce the sizes of input filters and to be beyond the audio frequency range. A practical dc supply would vary from its nominal value and an accaptable operating frequency range would specify the limit of dc voltage change. Figs. 3(a) and 3(b) show the variations of opearating frequency with ripple currents for +1 % and 5 % changes in dc input voltage, respectively.

Upto four choppers may be operated from a common filter as shown in Fig. 4.

With four choppers, the phase shift would be 45° and each chopper would operate with a duty cycle of 25%. The maximum peak to peak load current ripple occurs at 50% duty cycle and this should be avoided [3, 4]. For u choppers in multiphase operation, the maximum duty cycle of each chopper is 100/u % and this would increase the peak current rating of each chopper by approximately u%.

This controller is very simple. However for high current level, it would require parallel connection of transistors and this would increase the circuit complexity and reduce the efficiency. This controller does not permit electrical isolation of the magnets and the magnets may not be connected to the ground.

<u>Further Investigations:</u>

(i) To decide on the limits of acceptable operating frequency range.

(ii) To decide on the acceptable limits of magnet current ripple.

(iii) To decide on the acceptable regulations of dc input dc source.

(iv) Complete design of controllers to meet specifications of all magnets requiring uni-directional current control. This should include the ratings of power transistors (both BJTs and FETs), filter inductance, filter capacitance and the optimum number of multiphase choppers in a group.

(v) Cost and weight estimates of power circuits for all unidirectional magnet controllers.

2.2 Resonant Power Converter With Series Connected Load

The most reliable method for dc-dc conversion at a higher current level is to use a self-commutated thyristor inveter with a high frequency dc link. The first stage of conversion is a series resonant inverter. The ac output voltage is then converted to dc by a diode rectifier. The circuit diagram of a full-bridge inverter is shown in Fig. 5. The circuit operation can be divided into four modes.

Mode1: This mode begins when the thyristors T_1 and T_2 are turned on simultaneously. A resonant pulse of current flows through the dc source, T_1, T_2, C_m and L_m. At the same time, the magnet current is supplied from the load filter capcacitor C_o; and the current of inductor L_o falls. The equivalent circuit is shown in Fig. 6a. This mode ends when the resonant current equals to the current in inductor L_o.

Mode 2: This mode begins when the load referred to the transformer primary is placed in series with the resonant circuit. The energy is transferred to the load filter and load. The equivalent circuit is shown in Fig. 6b.

Mode 3: This mode begins when the voltage across the primary (and secondary) of the transfomer tends to be negative and two of the rectifier diodes conduct. The equivalent circuit is similar to that of mode 1, except the initial conditions are different. This mode ends when the resonant current falls to zero. Thyristors T_1 and T_2 are turned off due to self-commutation.

Mode 4: This mode begins when T_1 and T_2 are turned off. However, due to the energy stored in the circuit inductances, the resonant oscillation continues through feedback diodes D_1 and D_2. The process is similar to that in modes 1 to 3.

The waveform for the resonant current is shown in Fig. 7. By advancing the firing of thyristors, the resonant current (and hence the load current) can be varied. The thyristors and diodes should be replaced by reverse conducting thyristors (RCTs) for faster commutation of thyristors due to less stray inductance in the loop formed by a thyristor and its diode (e.g. T_1 and D_1).

During mode 2, the energy is transferred to the load circuit and the resonant frequency is changed. Due to inductor L_e which is normally large, the resonant frequency is reduced significantly and reduces the frequency of ac output. Since, the energy trasfer is done for a short time, the peak resonant current must be much larger than the load current.

Initial investigations of this circuit arrangement indicate that this arrangement may not be suitable.

<u>Further Investigations:</u>

Further study using computer model is necessary to:

(i) Establish the limits of the control characteristics.

(ii) Complete design of a controller to meet specifications for one type of magnet requiring unidirectional current control. This should include the ratings of RCTs, load filter inductance and capacitance, rectifier and isolating transformer.

(iii) Cost and weight estimates of power circuit for one unidirectional magnet controller.

2.3 Resonant Power Converter With Parallel Connected Load

The disadvantages of the circuit arrangement in Fig. 5 can be remedied by connecting the load circuit in parallel to the commutation capacitor as shown in Fig. 8. In this circuit, the voltage of the commutation capacitor is rectified and appears across the load circuit. The energy is transferred continuously from the resonant circuit to the load. The circuit operation can be divided into four modes.

Mode 1: This mode begins when thyristors T_1 and T_2 are fired. The resonant current continues to flow through the dc source, T_1, T_2, C_m and L_m. The load circuit is connected across C_m. This mode ends when the voltage of C_m falls to zero. The equivalent circuit for the this mode is shown in Fig. 9a.

Mode2 : This mode begins when the polarity of the voltage on C_m is positive and the direction of the load circuit connection is changed. The equivalent circuit is shown in Fig. 9b. Due the rectifier on the load circuit, the load filter inductor L_e is always connected to the positive terminal of C_m. At the end of this mode, the resonant current falls to zero; and T_1 and T_2 are turned off.

Mode 3: This mode begins when thyristors T_1 and T_2 are turned off and the resonant oscillation continues through the dc source, D_1, D_2, C_o and L_o. The equivalent circuit is similar to that of mode 2, except the intial conditions are different. This mode ends when the voltage on C_m falls to zero and the connection of the load circuit is changed.

Mode 4: This mode begins when the capacitor C_m is charged in the reverse direction and the connection of the load circuit is changed. The resonant oscillation of mode 3 continues. The equivalent circuit is similar to that of mode 1, except the intial conditions are different. This mode ends when the resonat current falls to zero.

With the firing of thyristors T_3 and T_4, the modes 1 to 4 are repeated. The waveforms for the resonant current, voltage on cappacitor C_m and output voltage of the rectifier are shown in Fig. 10.

If the electrical isolation of the magnet(s) is not critical, the load can be connected across the capacitor C_m without the isolating transformer as shown in Fig. 11. Since the resonant frequency is typically 20 kHz and filter inductance L_e is large, the impedance offered by the load would be high as compared that of C_m and as a result the load circuit would not have significant effect on the outout frequency.

Further Investigations:

Further study using computer model is necessary to:

(i) Establish the control characteristics.

(ii) Complete design of a controller to meet specifications for one type of magnet requiring unidirectional current control. This should include the ratings of RCTs, load filter inductance and capacitance, rectifier and isolating transformer.

(iii) Cost and weight estimates of power circuits for one unidirectioal magnet controller.

(iv) Decide between this circuit and the circuit of Fig. 5 (with a series connected load).

(v) Based on the outcome in part (iv) complete circuit design, cost and weight evaluations for all magnet controllers.

3. TWO-QUADRANT POWER CONTROLLERS

In a two-quadrant controller, the direction of the magnet current can be reversed. Such a controller can be implemented by (a) transistorized choppers, (b) (c) resonant inverter with a controlled rectifier link, and (c) resonant inverter with directly connected load.

3.1 Transistorized Two-Quadrant Chopper Control

The principle of one-quadrant chopper can be applied to two-quadrant operation. The circuit arrangement for two-quadrant operation is shown in Fig. 12 and this is an extension of Fig. 1.

Forward control: Q_1, Q_2 and D_1 operate. When Q_1 and Q_2 are turned on, the magnet is connected to the dc source and the magnet current rises. When Q_1 is turned off and Q_2 is still switched on, the magnet current decays through Q_2 and D_1.

Reverse control: Q_3, Q_4 and D_2 operate. When Q_3 and Q_4 are turned on, the magnet is connected to the dc source and the magnet current rises in opposite direction. When Q_3 is turned off and Q_4 is still switched on, the magnet current decays through Q_4 and D_2.

This arragement and its associated logic control are very simple. The characteristics of this two-quadrant controller would be similar to that of one-quadrant controller.

3.2 Resonant Inverter With Controlled Rectifier Link

The circuit diagram is shown in Fig. 13. The first stage is a half-bridge resonant inverter and the output of the inverter should be sinusoidal with a high frequency typically 20 kHz. Due to lower current requirement, a half-bridge inverter would be adequate. The second stage is a controlled rectifier. By varying the delay angles of thyristors T_1 and T_2, the dc output voltage across the magnet can be controlled and this voltage would be positive. On the other hand, if the delay angles of thyristors T_3 and T_4 are varied, a negative voltage would be applied to the magnet. The voltage waveforms are shown in Fig. 14.

This arragement requires a transformer and a controlled rectifier (and logic control circuit).

<u>Further Investigations:</u>

Further study by using computer model is necessary to

(i) Establish the control characteristics.

(ii) Complete the design of controllers to meet specifications for all magnets requiring bidirectional current control. This should include the ratings of RCTs, load filter inductance and capacitance, rectifier and transformer.

(iii) Cost and weight estimates of power circuits for all magnets.

3.3 Resonant Inverter With Directly Connected Load

A full-bridge resonant inverter where the magnet is connected directly across the commutation capacitor C_m is shown in Fig. 15. For positve magnet current, thyristors T_1 and T_2 are operative. When T_1 and T_2 are turned on, a resonant current flows through the circuit formed by the dc source, C_m, L_m, T_1 and and T_2. When the resonant current falls to zero, the resonant oscillation would continue through D_1 and D_2. Since, the time constant of the magnet is very large compared to the period of resonant oscillation, the current flow through the magnet should be unidirectional. It would be necessary to add a LC output filter to supply a continuous current to the magnet. The waveforms for the resonant current and capacitor voltage are shown in Fig. 16.

For negative magnet current, thyristors T_3 and T_4 would be operative.

This arragement does not require any rectifier and transformer. The same power circuit can be used for unidirectional and bidirectional current control. Only the logic control need to be chaged or programmed.

Further Investigations:

Further study is required to

(i) Establish the control characteristics.

(ii) Complete the design of controllers to meet specifications for all magnets requiring bidirectional current control. This should include the ratings of RCTs, load filter inductance and capacitance.

4. CONCLUSIONS

This study has explored the various possible alternatives to meet control requirements and proposes new circuit topologies which are suitable for magnet control. Each circuit arrangement has its advantages and disadvantages. However, the decision in choosing a circuit would depend on the circuit complexity, cost and weight. Each circuit should be analyzed in details and designed to establish its limitations and to make comparative evaluations in terms of desirable features.

For one-quadrant control, the manget current requirement varies from 145 A to 430 with dc voltgae requiremt of 16 V to 26 V. Chopper control with power transistors may be employed to all unidirectional controllers, epecially for 145 A magnet. Resonat pulse controller of Fig. 8 or 11 should be the choice for 430 A magnets.

For two-quadrant control. the current requirement varies from 57 A to 102 A at dc voltage of + 12 V to + 28 V. Transistorized two-quadrant chopper control could be used, epecially for 57 A and 70 A magnets. For 102 magnets, the resonant controller of Fig. 15 may be the alternative choice.

The characteristics of one-quadrant transistorized controller are fully analyzed by developing computer-aided models in a IBM PC. These models can be used to design the ratings of power devices and to investigate the effects of parameter variations.

Power transistorized circuits require carefull designs, because the transistors are very sensitive to peak transient voltages during the turn-off process. Whereas, for a properly designed thyristorized resonant inverter, the turn-off is almost guaranted and thyristors have much more over-rating capability.

The next stages of investigations would be:

(i) to establish the control characteristics of all circuit arrangements,

(ii) the design of power circuits to meet specifications for all magnets,

(iii) to estimate the costs and weights of all circuit arrangements,

(iv) the selection of the best circuit arragements, and

(v) more accurate computer models to evaluate the steady-state and dynamic performance of the controllers.

5. REFERENCES

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Table 1

Magnet Power Supplies for Storage Ring

		Rating				$\Delta I/I_{max}$		Magnet Parameters					
Magnet Circuit	No. of Units	I (A)	V (V)	P (kW)	Current Range	Stability	Reproducibility	R (Ω)	L (mH)	L/R (ms)	V (V)	I (A)	P (W)
Correction Dipole	64	57	±12	0.7	$\pm 10^3$:1	$\pm 2\times10^{-4}$	$\pm 2\times10^{-4}$	202	13	64	10.8	54	0.6
Quadrupole, 0.5 m	256	430	16	6.9	4:1	$\pm 1\times10^{-5}$	$\pm 2\times10^{-5}$	31	18	581	11.1	359	4
Quadrupole, 0.9 m	64	430	26	11.0	4:1	$\pm 1\times10^{-5}$	$\pm 2\times10^{-5}$	51	32	627	18.3	359	6.6
Sextupole	224	145	25	3.6	20:1	$\pm 1\times10^{-4}$	$\pm 2\times10^{-4}$	150	45	300	17.8	119	2.1
Sextupole Dipole V-Correction	224	102	±28	2.9	$\pm 10^3$:1	$\pm 3\times10^{-4}$	$\pm 4\times10^{-4}$	236	15	64	23.4	99	2.3
Dipole H-Correction	192	70	±14	1	$\pm 10^3$:1	$\pm 3\times10^{-4}$	$\pm 4\times10^{-4}$	11	2	182	11.5	67.3	0.8

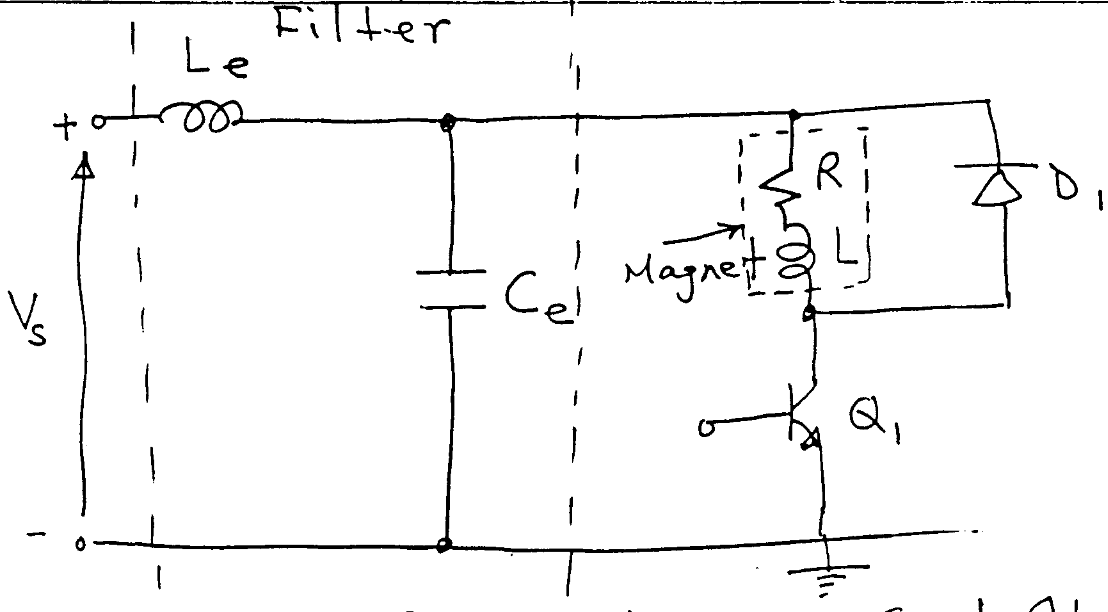


Fig. 1 Chopper Controller

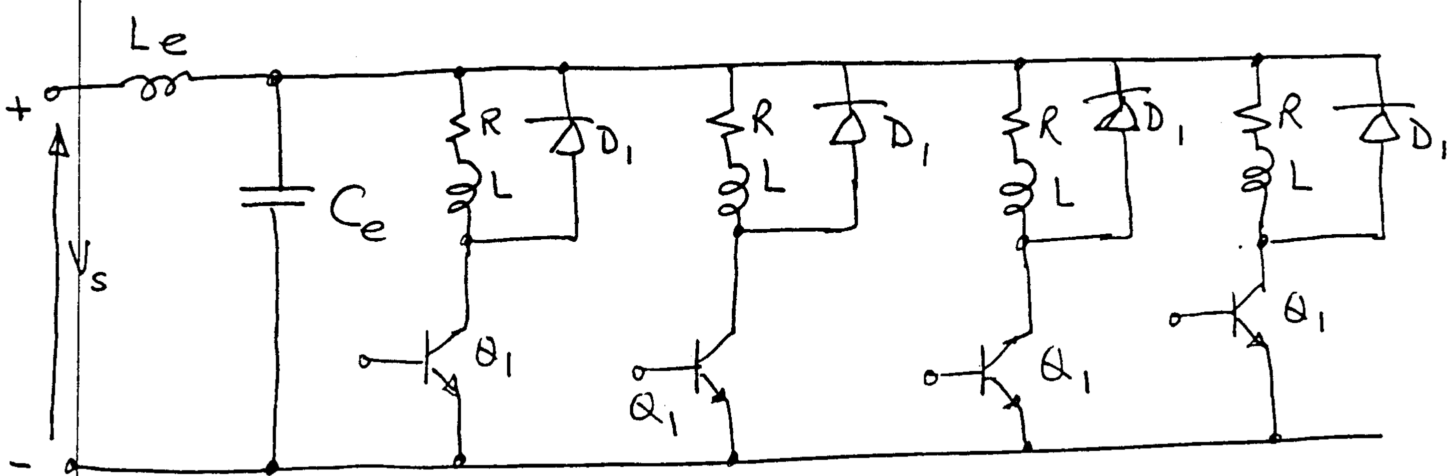


Fig. 4 Multiphase choppers

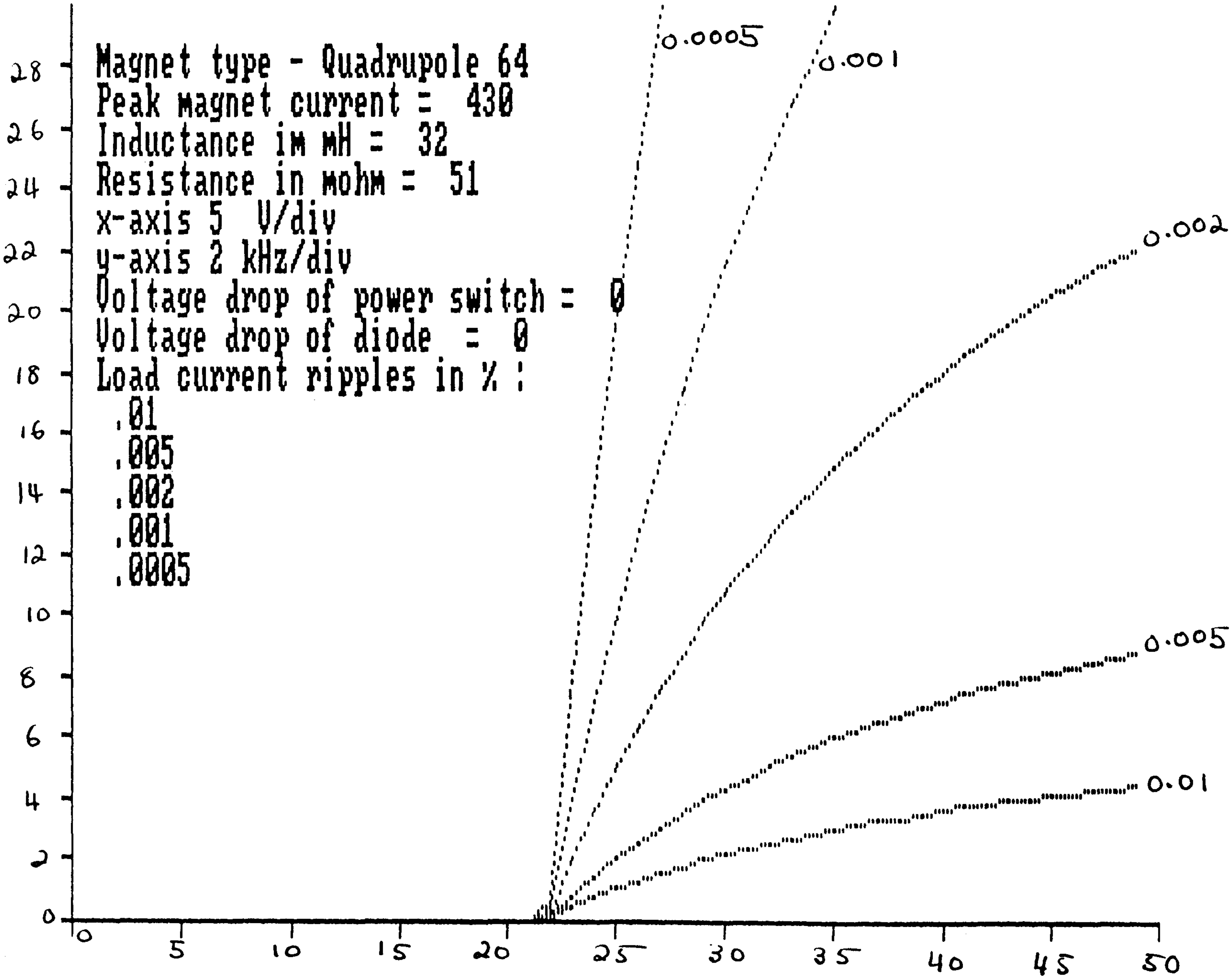

Magnet type - Quadrupole 64
Peak magnet current = 430
Inductance im mH = 32
Resistance in mohm = 51
x-axis 5 V/div
y-axis 2 kHz/div
Voltage drop of power switch = 0
Voltage drop of diode = 0
Load current ripples in % :
.01
.005
.002
.001
.0005
0.0005
0.001
0.002
0.005
0.01
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
5
10
15
20
25
30
35
40
45
50

Fig. 2 (a)

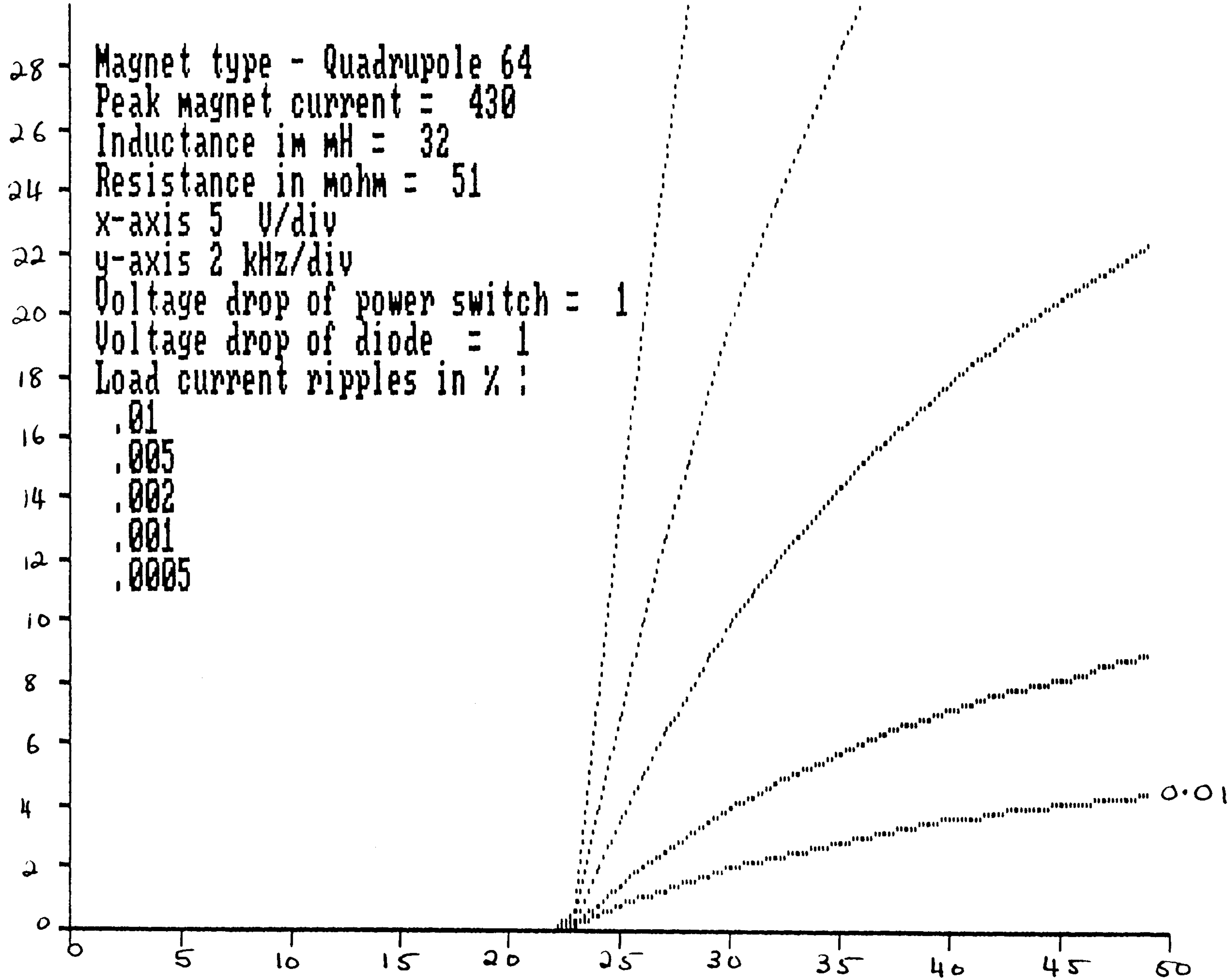

Magnet type - Quadrupole 64
Peak magnet current = 430
Inductance im mH = 32
Resistance in mohm = 51
x-axis 5 V/div
y-axis 2 kHz/div
Voltage drop of power switch = 1
Voltage drop of diode = 1
Load current ripples in % :
.01
.005
.002
.001
.0005
0.01
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
5
10
15
20
25
30
35
40
45
50

Fig. 2 (b)

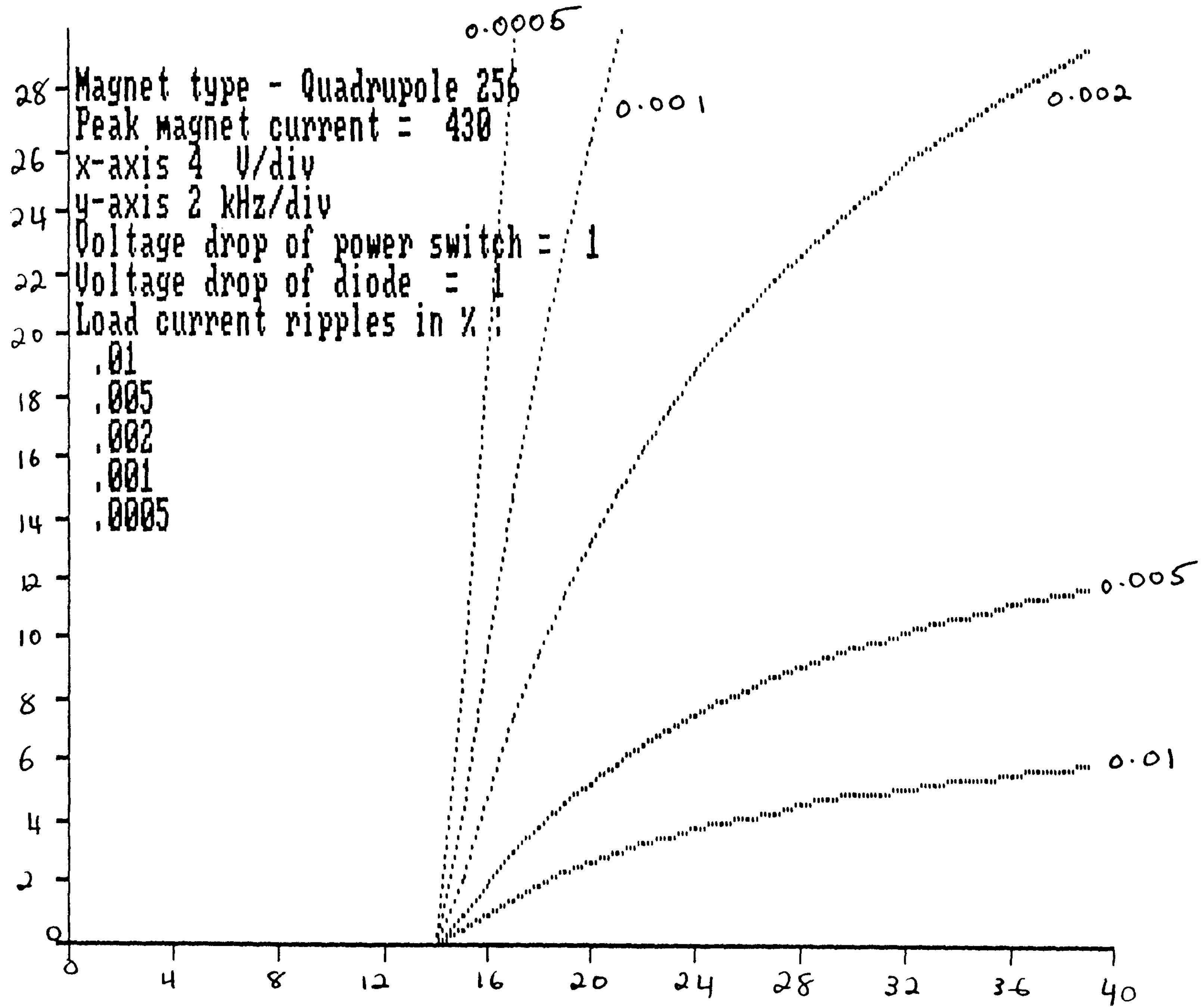

Magnet type - Quadrupole 256
Peak magnet current = 430
x-axis 4 V/div
y-axis 2 kHz/div
Voltage drop of power switch = 1
Voltage drop of diode = 1
Load current ripples in % :
.01
.005
.002
.001
.0005
0.0005
0.001
0.002
0.005
0.01
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
0
4
8
12
16
20
24
28
32
36
40

Fig. 2(c)

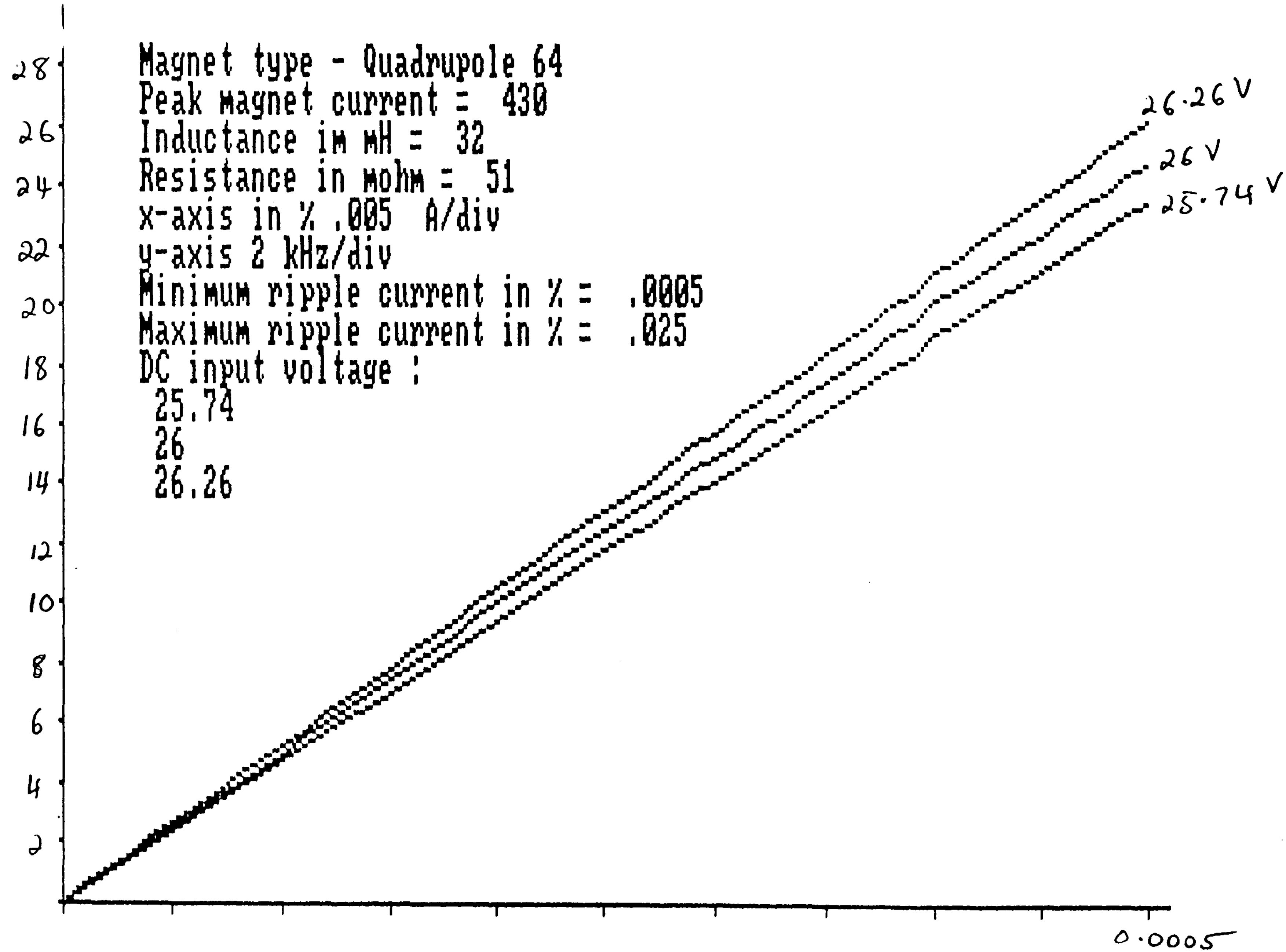
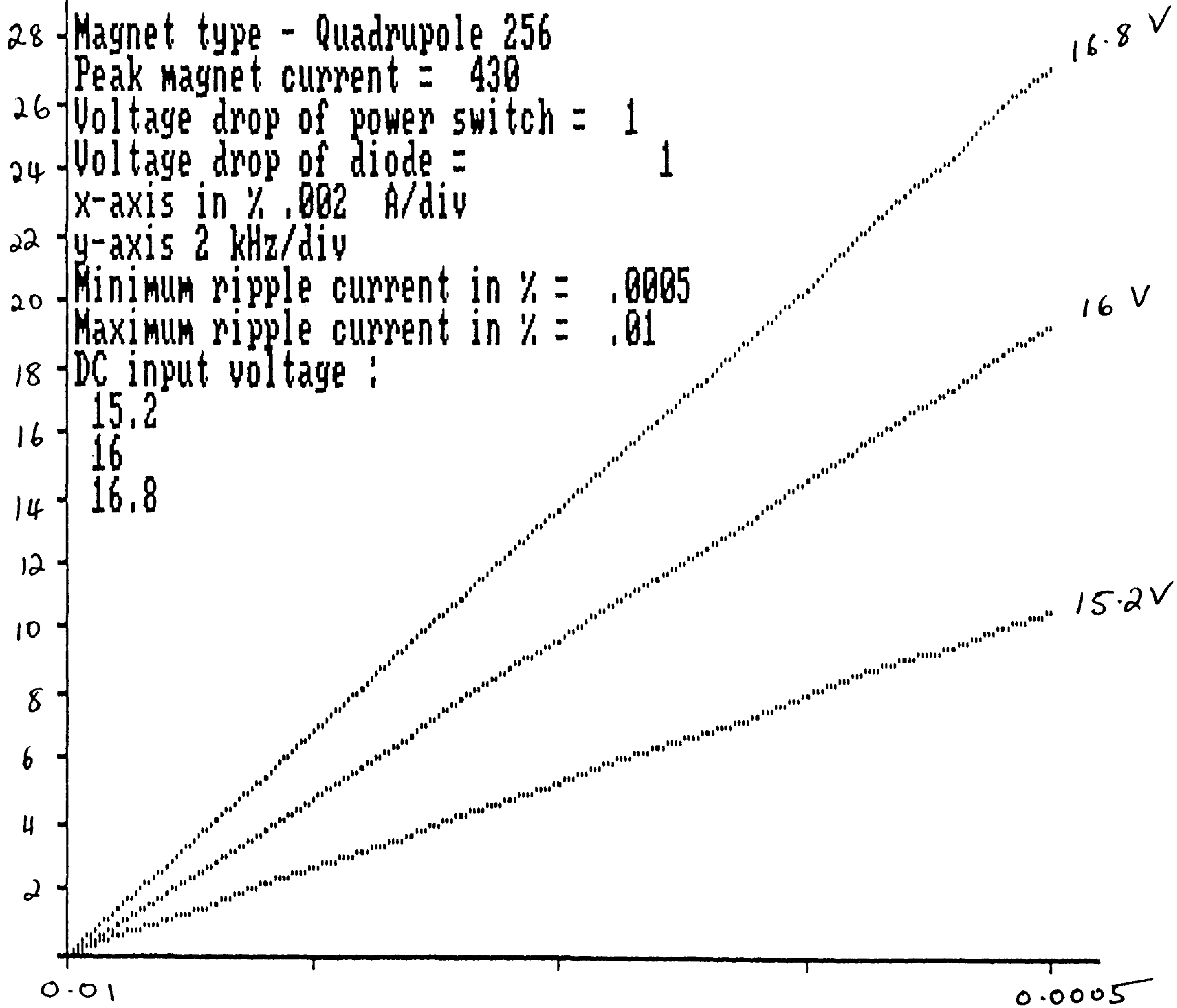

Magnet type - Quadrupole 64
Peak magnet current = 430
Inductance im mH = 32
Resistance in mohm = 51
x-axis in % .005 A/div
y-axis 2 kHz/div
Minimum ripple current in % = .0005
Maximum ripple current in % = .025
DC input voltage :
25.74
26
26.26
26.26 V
26 V
25.74 V
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0.0005

Fig. 3 (a)

22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Peak magnet current = 430
Voltage drop of power switch = 1
Voltage drop of diode = 1
x-axis in % .002 A/div
y-axis 2 kHz/div
Minimum ripple current in % = .0005
Maximum ripple current in % = .01
DC input voltage :
15.2
16
16.8
16.8 V
16 V
15.2V
28
26
24
22
20
18
16
14
12
10
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4
2
0.01
0.0005

Fig.3 (b)

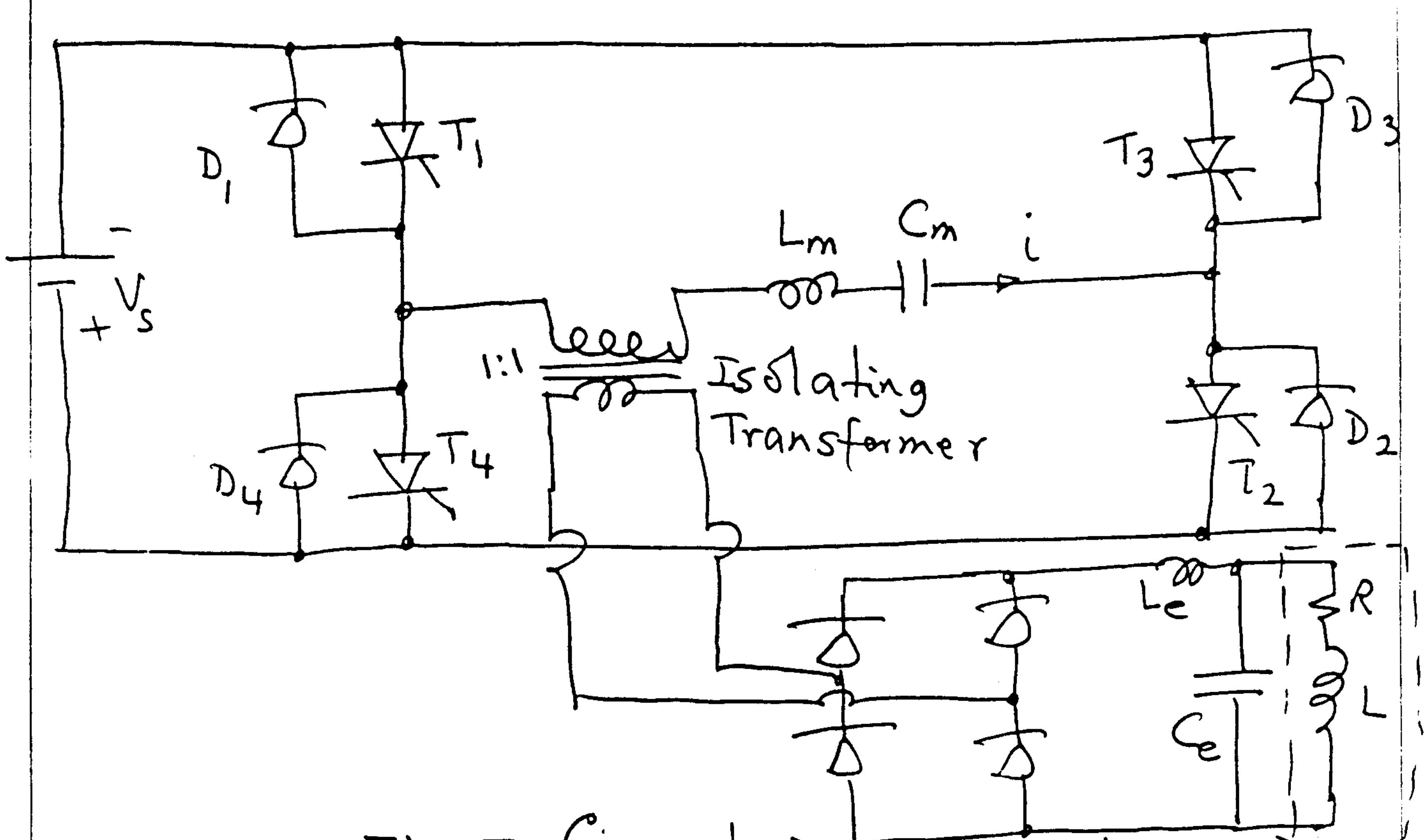
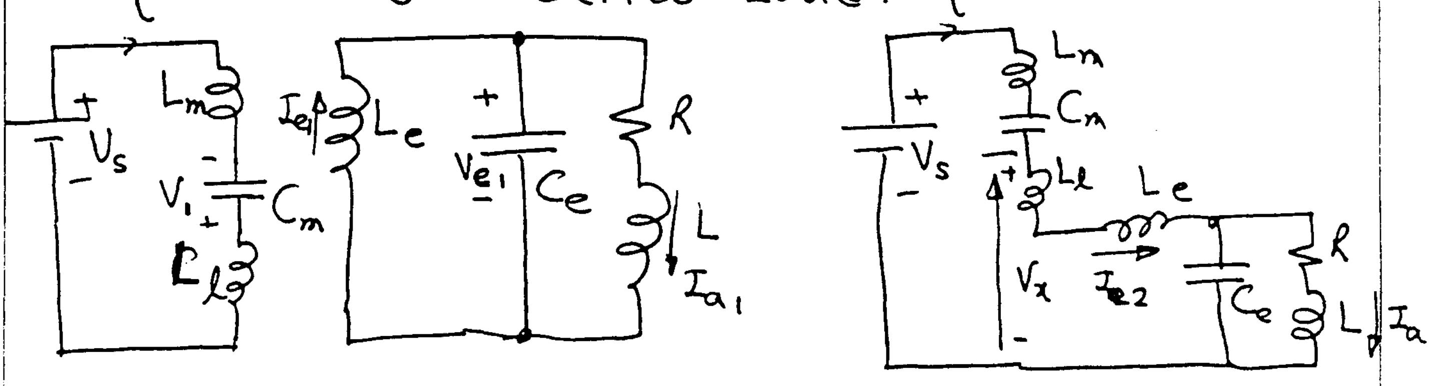


Fig. 5 Circuit Diagram with Magnet Series Load.



(a) Mode 1

(b) Mode 2

Fig. 6 Equivalent Circuits

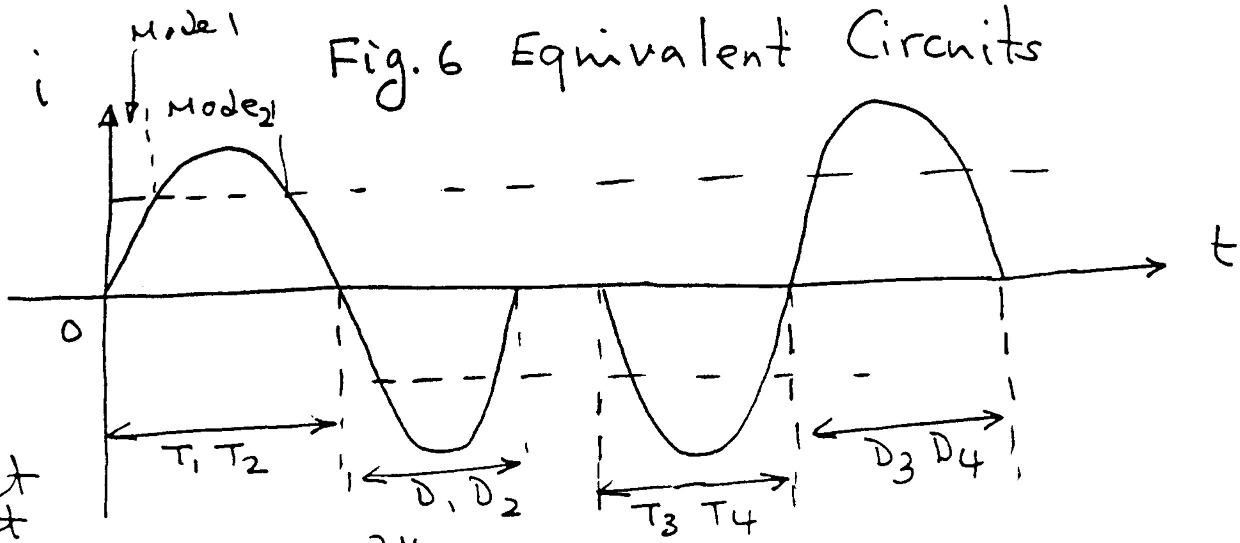


Fig. 7 Resonant Current

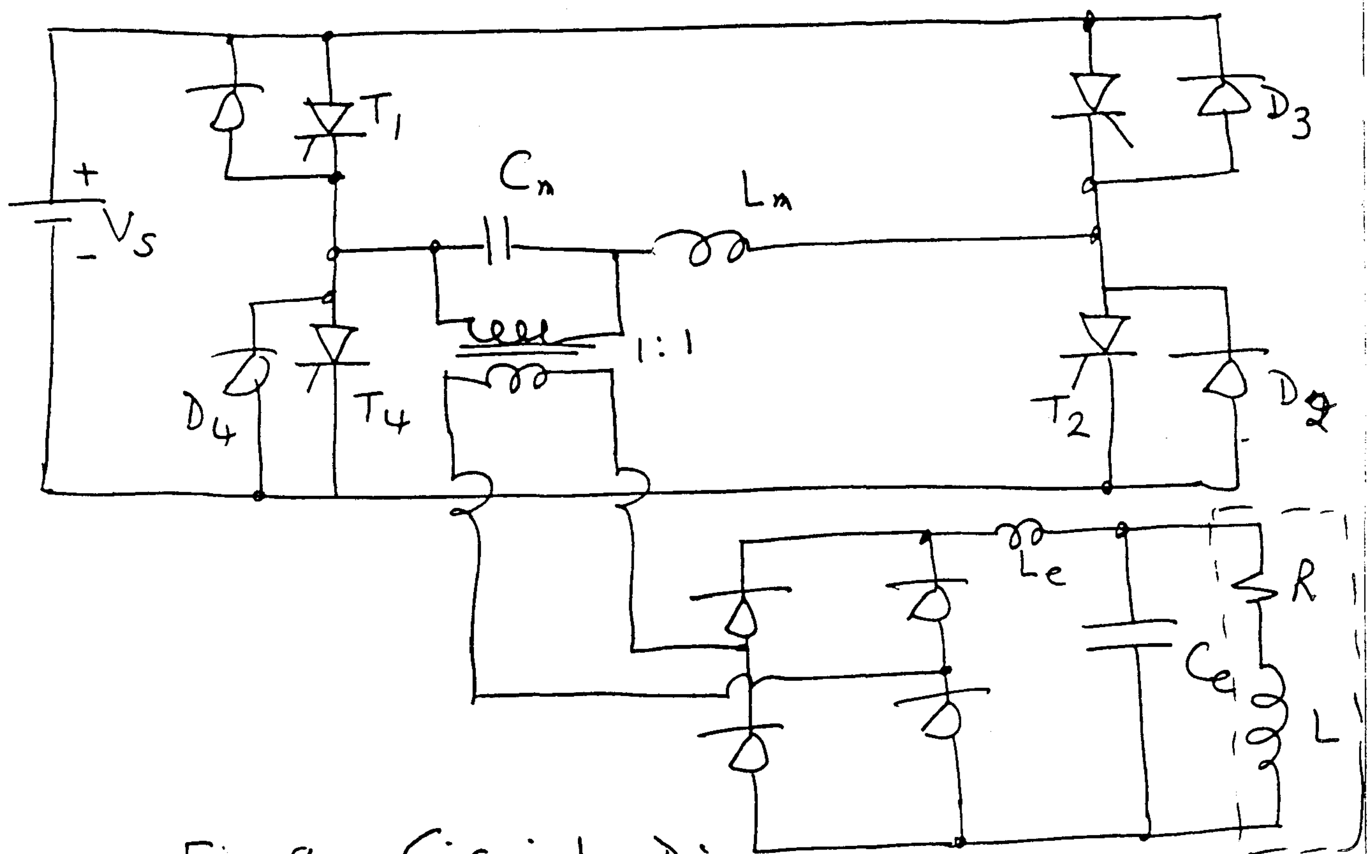
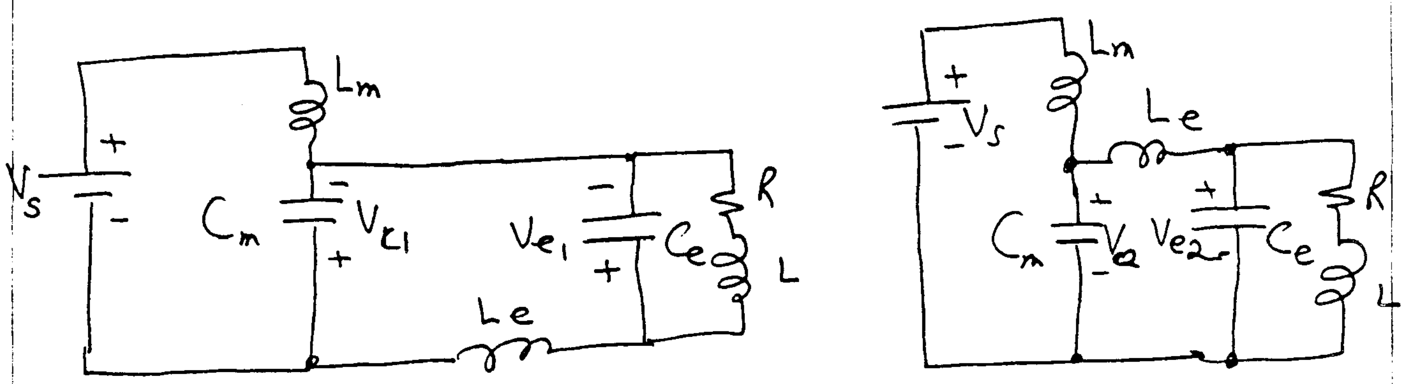


Fig. 8 Circuit Diagram with Parallel Load



(a) Mode 1

(b) Mode 2

Fig. 9 Equivalent Circuits

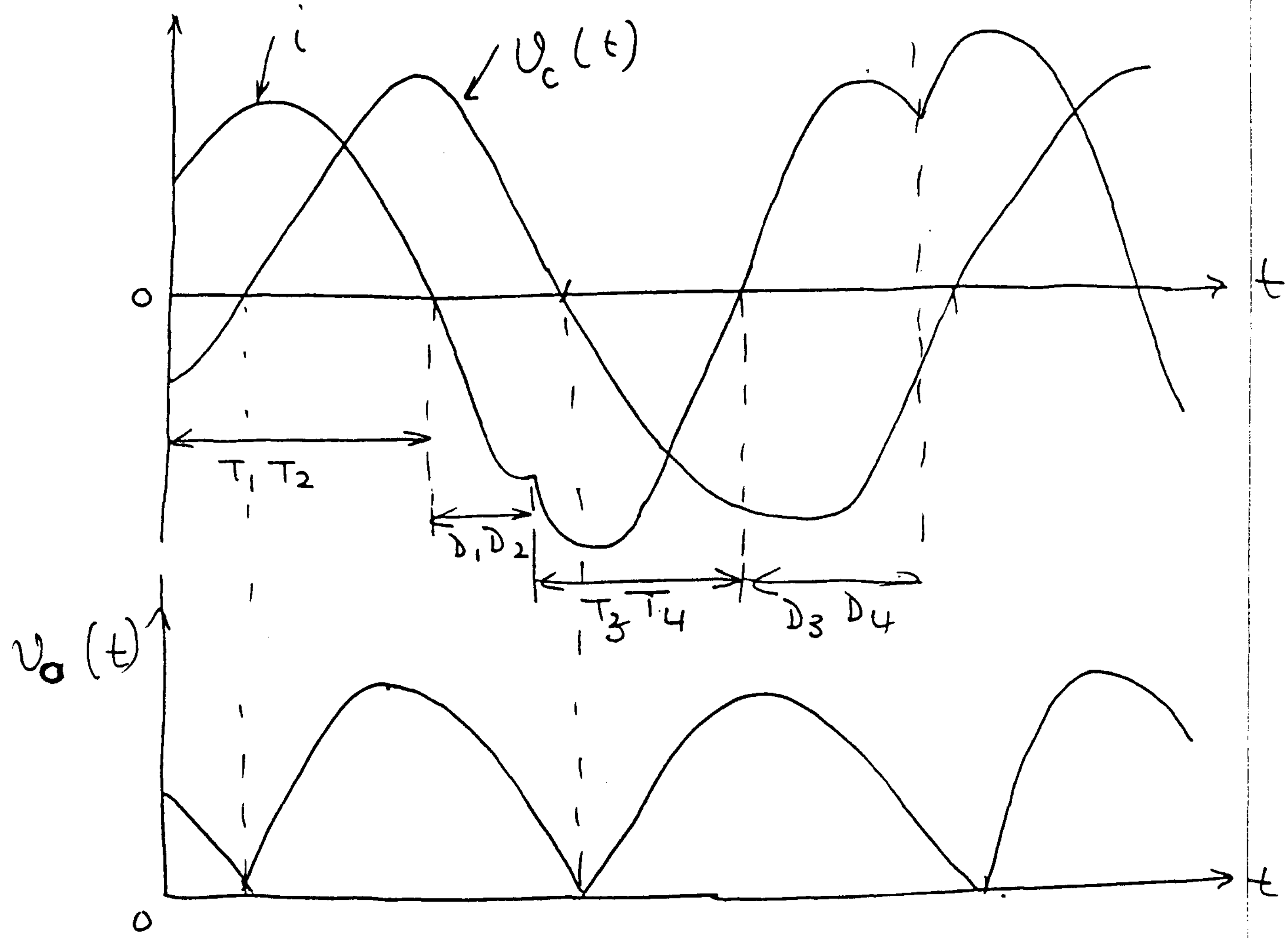


Fig. 10 Output waveforms

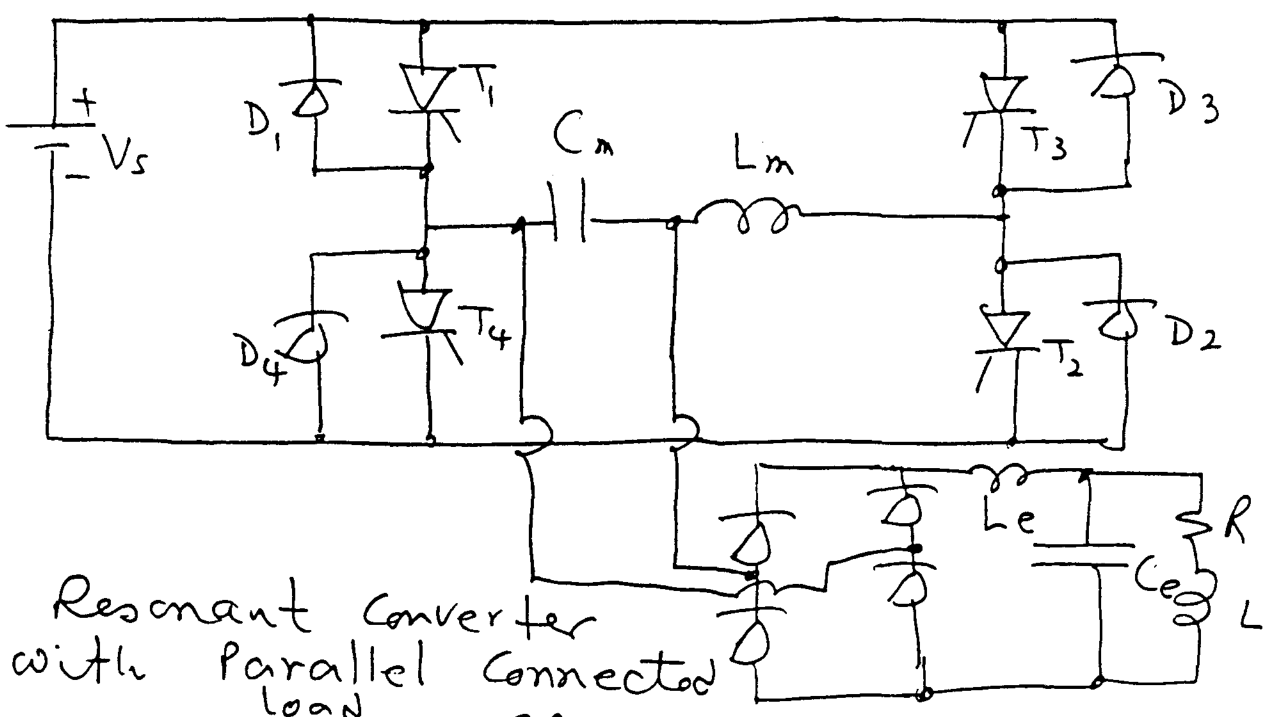


Fig. 11 Resonant Converter with Parallel Connected load

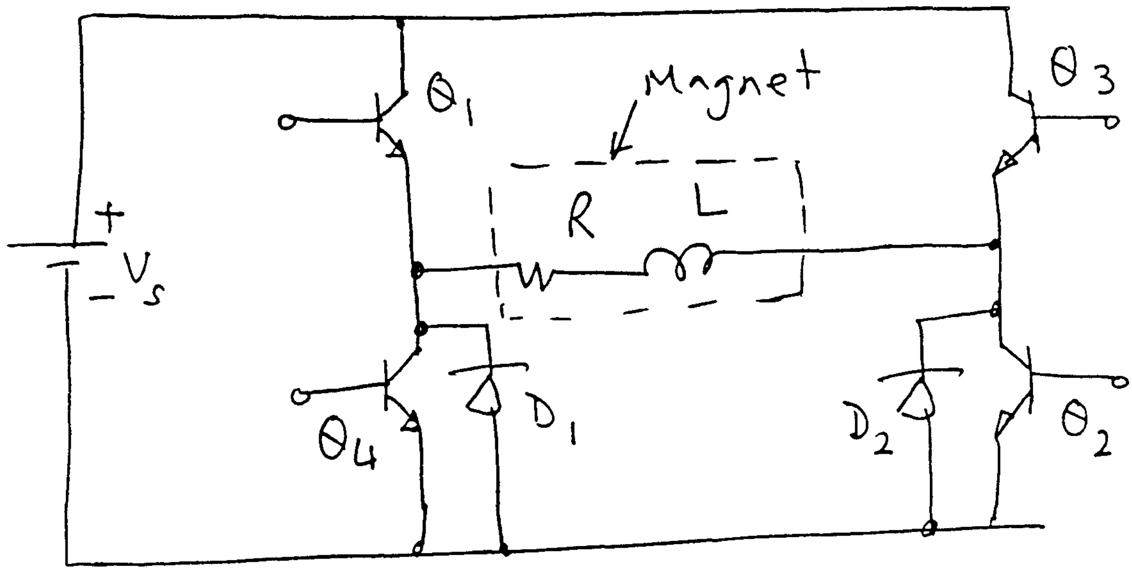


Fig. 12 Two-quadrant controller

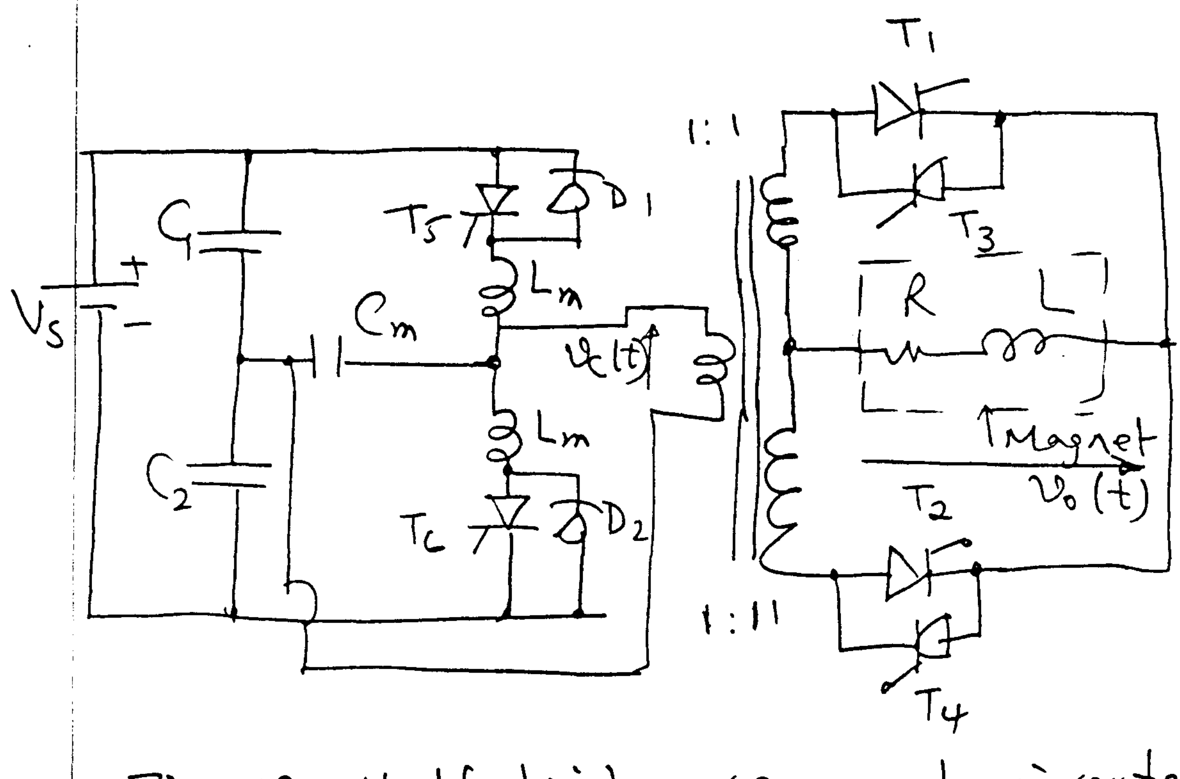


Fig. 13 Half-bridge resonant inverter with controlled Rectifr Link

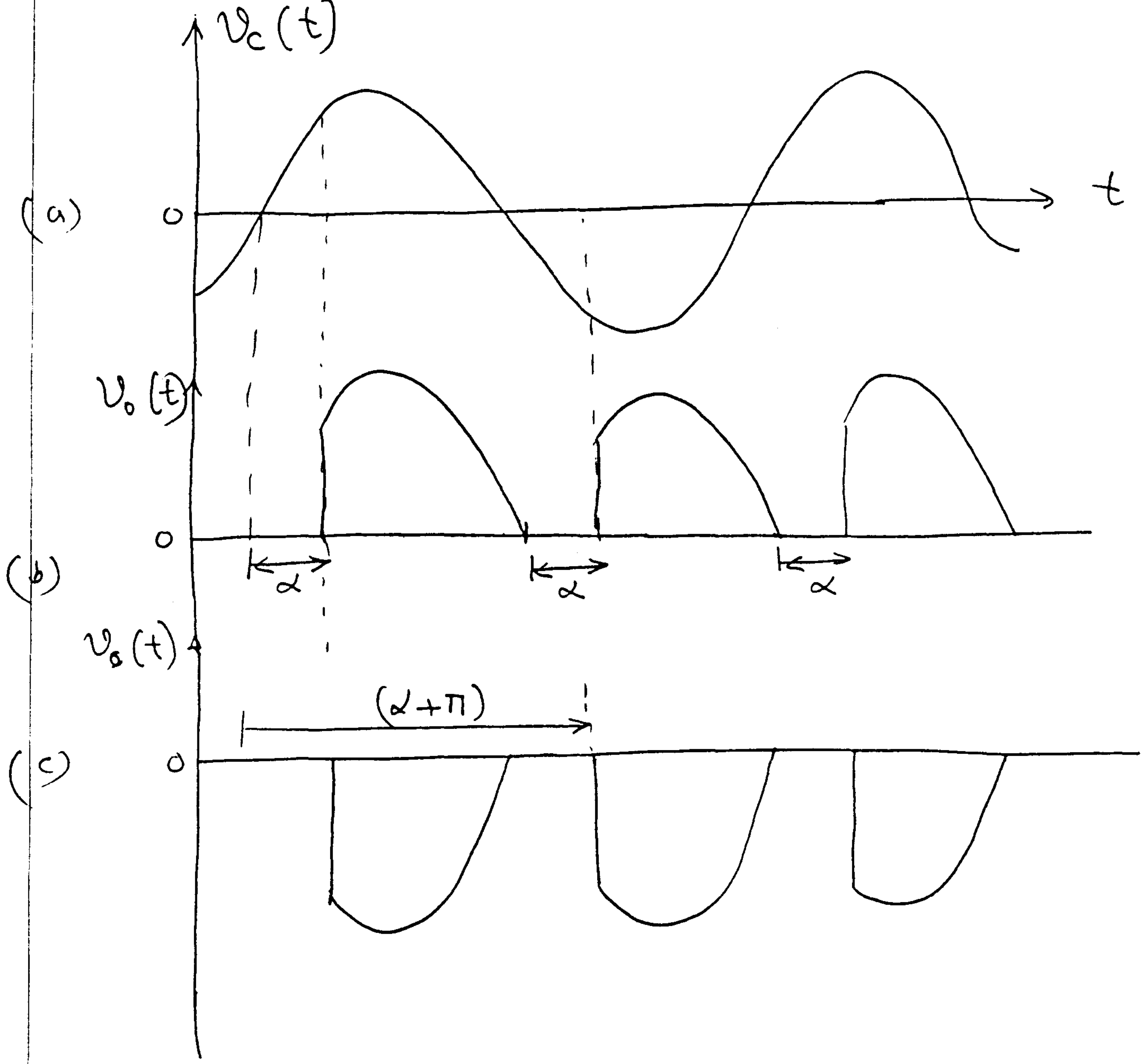


Fig. 14 Output waveforms

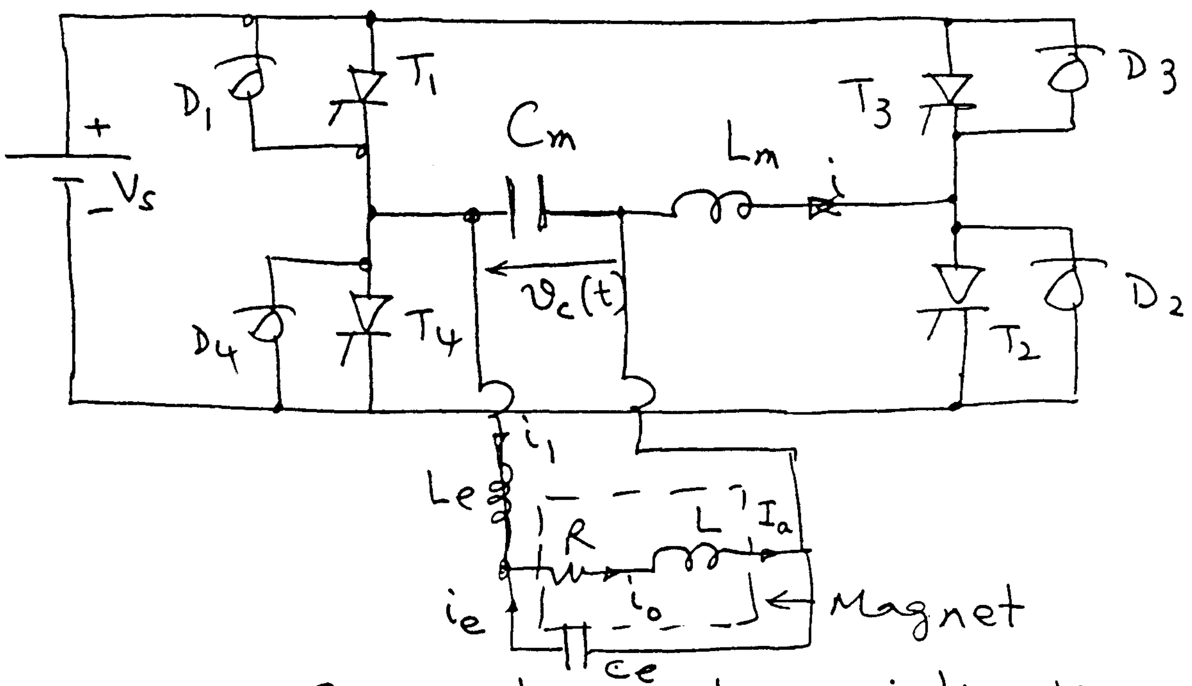


Fig. 15 Resonant inverter with directly Connected Load.

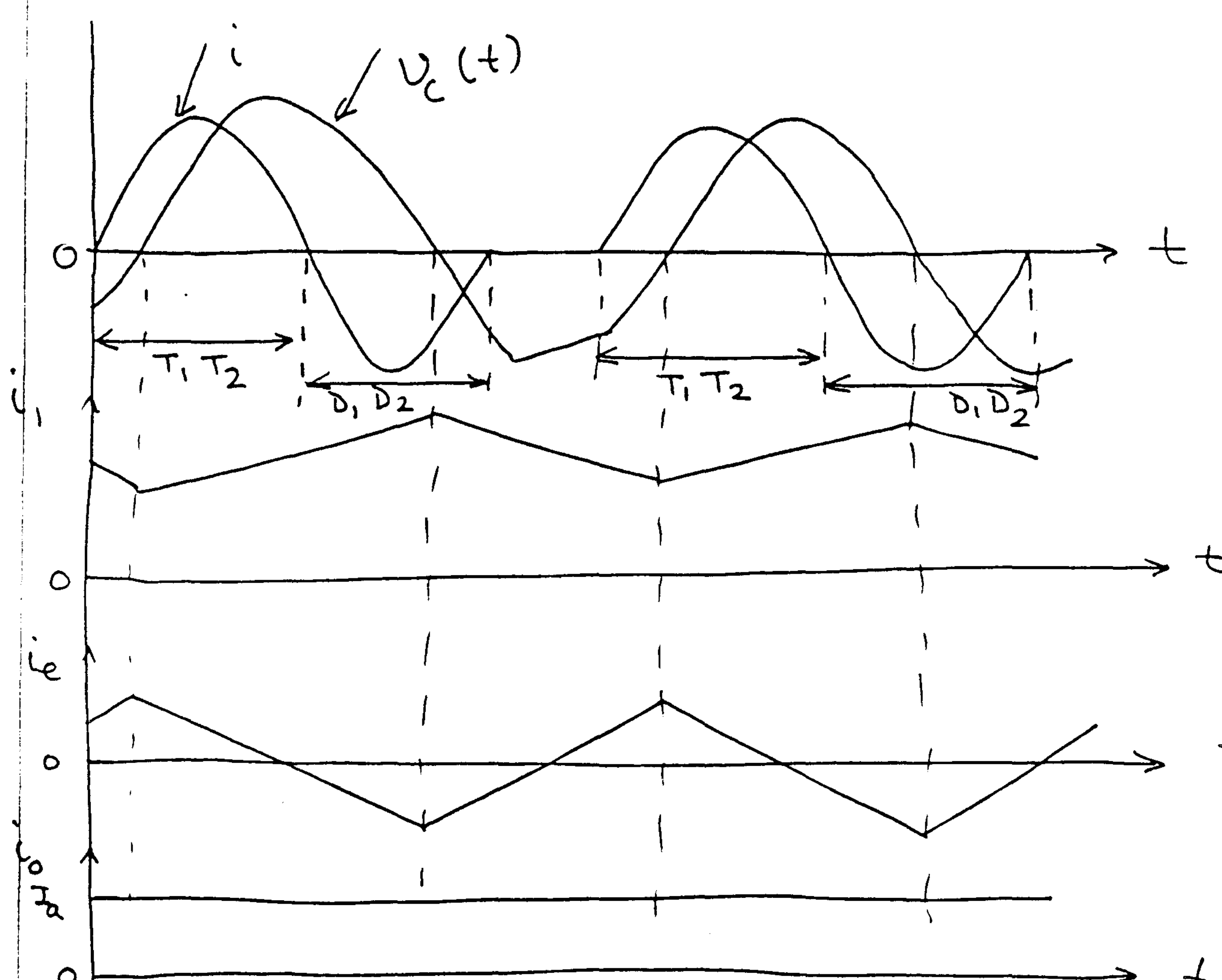


Fig. 16 Waveforms for voltages and currents

6. APPENDIX

Program Name: QQ-256

```
   REM Program Name:  QQ-256
8  CLS
10 DIM X(900), Y(900,12), DELX(10)
15 PRINT
20 PRINT "This program calculates the variations of frequency against the dc
30 PRINT "source. Magnet type - Quadrupole 256 "
34 PRINT
40 PRINT "Program Name 'QQ-256' "
45 PRINT
50 PRINT "DO YOU WANT A PLOT ONLY ?, IF YES '1' FOR NO '2' "
60 INPUT INX
110 PRINT "PEAK LOAD CURRENT ?"
120 INPUT IP
122 PRINT "HOW MANY RIPPLE CALCULATIONS ARE REQUIRED - MAXIMUM OF 10 ?"
124 INPUT KK
126 FOR J=1 TO KK
130 PRINT "LOAD CURRENT", J"TH RIPPLE AS % OF AVERAGE CURRENT ?"
140 INPUT DELX(J)
142 NEXT J
145 PRINT "MAXIMUM LIMIT OF DC INPUT VOLTAGE, NOT MORE THAN 40 V ? "
147 INPUT VX
170 PRINT "LOAD INDUCTANCE IN mH ?"
180 INPUT LA
190 LA=LA/1000
194 PRINT "LOAD RESISTANCE IN MILIOHM ? "
[illegible] INPUT RA
200 PRINT "VOLTAGE DROP OF POWER SWITCH ?"
205 INPUT VT
210 PRINT "VOLTAGE DROP OF FREE-WHEELING DIODE ?"
212 PRINT "LAST DATA INPUT ???????? "
215 INPUT VD
260 RA=RA/1000!
262 CLS
265 FOR M=1 TO KK
266 PRINT
267 PRINT "Magnet type - Quadrupole 256 "
270 PRINT "PEAK LOAD CURRENT = ", IP
273 DEL=.01*DELX(M)
275 IA=IP/(1+DEL)
280  DELA=DEL*IA
285 PRINT "LOAD CURRENT RIPPLE AS % OF AVERAGE CURRENT = " DELX(M)
290 PRINT "LOAD CURRENT RIPPLE = + ", DELA
300 PRINT "AVERAGE LOAD CURRENT = ",IA
310 PRINT "LOAD INDUCTANCE IIN mH = ", LA*1000
320 PRINT "LOAD RESISTANCE IN mH = ", RA*1000
322 PRINT "VOLTAGE DROP OF POWER SWITCH = " VT
324 PRINT "VOLTAGE DROP OF FREE-WHEELING DIODE = " VD
333 N=INT(VX)
335 J=0
338 VS=1!*J
[illegible] I2=IP
[illegible] I1=IA-DELA
360 Z#=I1-(VS-VD)/RA
370 C#=I2-(VS-VT)/RA
```

```
380 T1#=(LA/RA)*LOG(Z#/C#)
390 Z#=I1+VD/RA
400 C#=I2+VT/RA
410 T2#=(LA/RA)*LOG(C#/Z#)
420 T#=T1#+T2#
430 F=1/T#
440 K=T1#/T#
450 X(J)=J*1!
460 Y(J,M)=F/1000
470 IF Y(J,M)<0 THEN Y(J,M)=0
480 IF J>=N THEN 590
490 J=J+1
495 GOTO 338
590 PRINT "MAXIMUM DC INPUT VOLTAGE = ", VS
600 PRINT "MAXIMUM OPERATING FREQUENCY FOR THE MAXIMUM VOLTAGE = ", F
610 PRINT "DUTY CYCLE FOR MAXIMUM DC VOLTAGE IN % = ", 100*K
615 T11=T1#
620 PRINT "ON TIME IN us = ", T11*1000000!
622 NEXT M
625 IF INX=2 GOTO 800
627 CLS
628 PRINT : PRINT
629 DIV=VX/10
631 KEY OFF
632 LOCATE 2,1
634 PRINT SPC(7) "Magnet type - Quadrupole 256 "
635 PRINT SPC(7) "Peak magnet current = "IP
638 PRINT SPC(7) "x-axis" DIV " V/div "
639 PRINT SPC(7) "y-axis 2 kHz/div"
641 PRINT SPC(7) "Voltage drop of power switch = "VT
642 PRINT SPC(7) "Voltage drop of diode  = "VD
644 PRINT SPC(7) "Load current ripples in % :"
646 FOR J=1 TO KK
647 PRINT SPC(7) DELX(J)
648 NEXT J
649 SCREEN 2
650 WINDOW (-4,-2)-(45,30)
660 LINE (0,0)-(40,0)
670 LINE (0,30)-(0,0)
680 FOR M=1 TO KK
690 FOR J=1 TO N-1
700 LINE -(X(J),Y(J,M)),,,&HAAAA
710 NEXT J
712 LINE (0,0)-(0,0)
715 NEXT M
720 FOR N=0 TO 40 STEP 4
730 LINE (N,0)-(N,-.6)
740 NEXT N
750 FOR N=0 TO 28 STEP 2
*760 LINE (0,N)-(-.5,N)
770 NEXT N
800 END
```

Program Name: QQ-256A

```
1  CLS
```

```
2  REM Program Name:  QQ-256A
3  PRINT "Program name 'QQ-256A' "
4  PRINT
[illegible]  PRINT "This program calculates the variations of frequency against
5  PRINT
6  PRINT "the ripple current. Magnet type - Quadrupole 256."
8  PRINT
10 DIM X(500), Y(500,5), DVX(5)
50 PRINT "DO YOU A PLOT ONLY ?, IF YES '1' FOR NO '2' "
60 INPUT INX
110 PRINT "PEAK LOAD CURRENT ?"
120 INPUT IP
122 PRINT "WHAT IS THE RATIO OF MAXIMUM TO MINIMUM RIPPLE CURRENT ?"
124 INPUT KK
130 PRINT "MINIMUM LOAD CURRENT RIPPLE AS % OF AVERAGE CURRENT ? "
140 INPUT DELX
145 PRINT "NOMINAL VALUE OF DC INPUT VOLTAGE  ?"
147 INPUT VX
150 PRINT "REGULATION OF DC INPUT VOLTAGE ?"
155 INPUT DVS
160 DELVS=.01*VX*DVS
170 PRINT "LOAD INDUCTANCE IN mH ?"
180 INPUT LA
190 LA=LA/1000
194 PRINT "LOAD RESISTANCE IN MILIOHM ? "
198 INPUT RA
200 PRINT "VOLTAGE DROP OF POWER SWITCH ?"
205 INPUT VT
2[illegible] PRINT "VOLTAGE DROP OF FREE-WHEELING DIODE ?"
2[illegible] PRINT "LAST DATA INPUT ???????? "
215 INPUT VD
220 RA=RA/1000!
225 CLS
230 FOR M=1 TO 3
235 VS=VX-DELVS*(2-M)
237 DVX(M)=VS
240 PRINT
245 PRINT "Magnet type - Quadrupole 256."
246 PRINT "PEAK LOAD CURRENT = " IP
248 PRINT "LOAD INDUCTANCE IIN mH = " LA*1000
250 PRINT "LOAD RESISTANCE IN mH = " RA*1000
252 PRINT "VOLTAGE DROP OF POWER SWITCH = " VT
254 PRINT "VOLTAGE DROP OF FREE-WHEELING DIODE = " VD
255 KM=KK+1
260 FOR J=1 TO KM
265 DEL=.01*DELX*KK/J
275 IA=IP/(1+DEL)
280 DELA=DEL*IA
333 N=INT(VX)
340 I2=IP
350 I1=IA-DELA
360 Z#=I1-(VS-VD)/RA
370 C#=I2-(VS-VT)/RA
3[illegible] T1#=(LA/RA)*LOG(Z#/C#)
3[illegible] Z#=I1+VD/RA
400 C#=I2+VT/RA
410 T2#=(LA/RA)*LOG(C#/Z#)
420 T#=T1#+T2#
```

```
430 F=1!/T#
440 K=T1#/T#
450 X(J)=J*1!
460 Y(J,M)=F/1000
470 IF Y(J,M)<0 THEN Y(J,M)=0
475 IF Y(J,M)<=0 THEN 621
480 PRINT "LOAD CURRENT RIPPLE AS  % OF AVERAGE CURRENT = "DEL*100!
485 PRINT "LOAD CURRENT RIPPLE = +"DELA
488 PRINT "AVERAGE LOAD CURRENT = "IA
590 PRINT "DC INPUT VOLTAGE = "VS
600 PRINT "MAXIMUM OPERATING FREQUENCY FOR THE MINIMUM RIPPLE CURRENT =" F
610 PRINT "DUTY CYCLE FOR MINIMUM RIPPLE CURRENT IN % = " 100*K
615 T11=T1#
620 PRINT "ON TIME IN us = ", T11*1000000!
621 NEXT J
622 NEXT M
625 IF INX=2 GOTO 800
627 CLS
628 DIV=DELX*KK/5!
629 SCREEN 2
631 KEY OFF
632 LOCATE 2,1
634 PRINT SPC(9) "Magnet type - Quadrupole 256 "
635 PRINT SPC(9) "Peak magnet current = "IP
636 PRINT SPC(9) "Voltage drop of power switch = "VT
637 PRINT SPC(9) "Voltage drop of diode = ",VD
638 PRINT SPC(9) "x-axis in %" DIV " A/div "
639 PRINT SPC(9) "y-axis 2 kHz/div"
640 PRINT SPC(9) "Minimum ripple current in % = "DELX
641 PRINT SPC(9) "Maximum ripple current in % = "DELX*KK
642 PRINT SPC(9) "DC input voltage :"
643 FOR J=1 TO 3
644 PRINT SPC(9) DVX(J)
645 NEXT J
648 KJ=KK+5
649 SCREEN 2
650 WINDOW (-3,-2)-(KJ,30)
660 LINE (0,0)-(KM,0)
670 LINE (0,30)-(0,0)
680 FOR M=1 TO 3
690 FOR J=1 TO KK
700 LINE -(X(J),Y(J,M)),,,&HAAAA
710 NEXT J
712 LINE (0,0)-(0,0)
715 NEXT M
720 FOR N=0 TO KK STEP 5
730 LINE (N,0)-(N,-.4)
740 NEXT N
750 FOR N=0 TO 28 STEP 2
760 LINE (0,N)-(-.2,N)
770 NEXT N
800 END
810 PRINT SPC(9) "DC input voltage :"
811 FOR J=1 TO 3
812 PRINT SPC(9) DVX(J)
813 NEXT J
--------------------------------------------------------------------------------
```

```
   REM Program Name:   QQ-64
8  CLS
10 DIM X(900), Y(900,12), DELX(10)
15 PRINT
20 PRINT "This program calculates the variations of frequency against the dc
30 PRINT "source. Magnet type - Quadrupole 64."
34 PRINT
40 PRINT "Program Name 'QQ-64' "
45 PRINT
50 PRINT "DO YOU A PLOT ONLY ?, IF YES '1' FOR NO '2' "
60 INPUT INX
110 PRINT "PEAK LOAD CURRENT ?"
120 INPUT IP
122 PRINT "HOW MANY RIPPLE CALCULATIONS ARE REQUIRED - MAXIMUM OF 10 ?"
124 INPUT KK
126 FOR J=1 TO KK
130 PRINT "LOAD CURRENT", J"TH RIPPLE AS % OF AVERAGE CURRENT ?"
140 INPUT DELX(J)
142 NEXT J
145 PRINT "MAXIMUM LIMIT OF DC INPUT VOLTAGE, NOT MORE THAN 50 V ? "
147 INPUT VX
170 PRINT "LOAD INDUCTANCE IN mH ?"
180 INPUT LA
190 LA=LA/1000
194 PRINT "LOAD RESISTANCE IN MILIOHM ? "
  3 INPUT RA
  0 PRINT "VOLTAGE DROP OF POWER SWITCH ?"
205 INPUT VT
210 PRINT "VOLTAGE DROP OF FREE-WHEELING DIODE ?"
212 PRINT "LAST DATA INPUT ???????? "
215 INPUT VD
260 RA=RA/1000!
262 CLS
265 FOR M=1 TO KK
266 PRINT
267 PRINT "Magnet type - Quadrupole 64."
270 PRINT "PEAK LOAD CURRENT = ", IP
273 DEL=.01*DELX(M)
275 IA=IP/(1+DEL)
280  DELA=DEL*IA
285 PRINT "LOAD CURRENT RIPPLE AS % OF AVERAGE CURRENT = " DELX(M)
290 PRINT "LOAD CURRENT RIPPLE = + ", DELA
300 PRINT "AVERAGE LOAD CURRENT = ",IA
310 PRINT "LOAD INDUCTANCE IIN mH = ", LA*1000
320 PRINT "LOAD RESISTANCE IN mH = ", RA*1000
333 N=INT(VX)
335 J=0
338 VS=1!*J
340 I2=IP
350 I1=IA-DELA
    Z#=I1-(VS-VD)/RA
    C#=I2-(VS-VT)/RA
380 T1#=(LA/RA)*LOG(Z#/C#)
390 Z#=I1+VD/RA
400 C#=I2+VT/RA
```

```
410 T2#=(LA/RA)*LOG(C#/Z#)
420 T#=T1#+T2#
430 F=1/T#
440 K=T1#/T#
450 X(J)=J*1!
460 Y(J,M)=F/1000
470 IF Y(J,M)<0 THEN Y(J,M)=0
480 IF J>=N THEN 590
490 J=J+1
495 GOTO 338
590 PRINT "MAXIMUM DC INPUT VOLTAGE = ", VS
600 PRINT "MAXIMUM OPERATING FREQUENCY FOR THE MAXIMUM VOLTAGE = ", F
610 PRINT "DUTY CYCLE FOR MAXIMUM DC VOLTAGE IN % = ", 100*K
615 T11=T1#
620 PRINT "ON TIME IN us = ", T11*1000000!
622 NEXT M
625 IF INX=2 GOTO 800
627 CLS
628 PRINT : PRINT
629 DIV=VX/10
631 KEY OFF
632 LOCATE 2,1
634 PRINT SPC(7) "Magnet type - Quadrupole 64 "
635 PRINT SPC(7) "Peak magnet current = "IP
636 PRINT SPC(7) "Inductance im mH = " 1000!*LA
637 PRINT SPC(7) "Resistance in mohm = " 1000!*RA
638 PRINT SPC(7) "x-axis" DIV " V/div "
639 PRINT SPC(7) "y-axis 2 kHz/div"
641 PRINT SPC(7) "Voltage drop of power switch = "VT
642 PRINT SPC(7) "Voltage drop of diode  = "VD
644 PRINT SPC(7) "Load current ripples in % :"
646 FOR J=1 TO KK
647 PRINT SPC(7) DELX(J)
648 NEXT J
649 SCREEN 2
650 WINDOW (-4,-2)-(55,30)
660 LINE (0,0)-(50,0)
670 LINE (0,30)-(0,0)
680 FOR M=1 TO KK
690 FOR J=1 TO N-1
700 LINE -(X(J),Y(J,M)),,,&HAAAA
710 NEXT J
712 LINE (0,0)-(0,0)
715 NEXT M
720 FOR N=0 TO 50 STEP 5
730 LINE (N,0)-(N,-.6)
740 NEXT N
750 FOR N=0 TO 28 STEP 2
760 LINE (0,N)-(-.5,N)
770 NEXT N
800 END
```

Program Name: QQ-64A

```
7  Program Name:  QQ-64A
8  CLS
```

```
10 DIM X(500), Y(500,5), DVX(5)
15 PRINT
   PRINT "This program calculates the variations of frequency against
30 PRINT "the ripple current. Magnet type - Quadrupole 64."
34 PRINT
36 PRINT "Program name 'QQ-64A' "
38 PRINT
50 PRINT "DO YOU A PLOT ONLY ?, IF YES '1' FOR NO '2' "
60 INPUT INX
110 PRINT "PEAK LOAD CURRENT ?"
120 INPUT IP
122 PRINT "WHAT IS THE RATIO OF MAXIMUM TO MINIMUM RIPPLE CURRENT ?"
124 INPUT KK
130 PRINT "MINIMUM LOAD CURRENT RIPPLE AS % OF AVERAGE CURRENT ? "
140 INPUT DELX
145 PRINT "NOMINAL VALUE OF DC INPUT VOLTAGE  ?"
147 INPUT VX
150 PRINT "REGULATION OF DC INPUT VOLTAGE ?"
155 INPUT DVS
160 DELVS=.01*VX*DVS
170 PRINT "LOAD INDUCTANCE IN mH ?"
180 INPUT LA
190 LA=LA/1000
194 PRINT "LOAD RESISTANCE IN MILIOHM ? "
198 INPUT RA
200 PRINT "VOLTAGE DROP OF POWER SWITCH ?"
205 INPUT VT
210 PRINT "VOLTAGE DROP OF FREE-WHEELING DIODE ?"
212 PRINT "LAST DATA INPUT ???????? "
215 INPUT VD
220 RA=RA/1000!
225 CLS
230 FOR M=1 TO 3
235 VS=VX-DELVS*(2-M)
237 DVX(M)=VS
240 PRINT
245 PRINT "Magnet type - Quadrupole 64."
250 PRINT "PEAK LOAD CURRENT = " IP
252 PRINT "LOAD INDUCTANCE IIN mH = " LA*1000
254 PRINT "LOAD RESISTANCE IN mH = " RA*1000
255 KM=KK+1
260 FOR J=1 TO KM
265 DEL=.01*DELX*KK/J
275 IA=IP/(1+DEL)
280 DELA=DEL*IA
333 N=INT(VX)
340 I2=IP
50 I1=IA-DELA
360 Z#=I1-(VS-VD)/RA
370 C#=I2-(VS-VT)/RA
380 T1#=(LA/RA)*LOG(Z#/C#)
390 Z#=I1+VD/RA
400 C#=I2+VT/RA
410 T2#=(LA/RA)*LOG(C#/Z#)
420 T#=T1#+T2#
430 F=1!/T#
440 K=T1#/T#
```

```
450 X(J)=J*1!
460 Y(J,M)=F/1000
470 IF Y(J,M)<0 THEN Y(J,M)=0
475 NEXT J
480 PRINT "LOAD CURRENT RIPPLE AS  % OF AVERAGE CURRENT = "DELX
485 PRINT "LOAD CURRENT RIPPLE = +"DELA
488 PRINT "AVERAGE LOAD CURRENT = "IA
590 PRINT "DC INPUT VOLTAGE = "VS
600 PRINT "MAXIMUM OPERATING FREQUENCY FOR THE MINIMUM RIPPLE CURRENT =" F
610 PRINT "DUTY CYCLE FOR MINIMUM RIPPLE CURRENT IN % = " 100*K
615 T11=T1#
620 PRINT "ON TIME IN us = ", T11*1000000!
622 NEXT M
625 IF INX=2 GOTO 800
627 CLS
628 DIV=DELX*KK/5!
629 SCREEN 2
631 KEY OFF
632 LOCATE 2,1
634 PRINT SPC(9) "Magnet type - Quadrupole 64 "
635 PRINT SPC(9) "Peak magnet current = "IP
636 PRINT SPC(9) "Voltage drop of power switch = "VT
637 PRINT SPC(9) "Voltage drop of diode = ",VD
638 PRINT SPC(9) "x-axis in %" DIV " A/div "
639 PRINT SPC(9) "y-axis 2 kHz/div"
640 PRINT SPC(9) "Minimum ripple current in % = "DELX
641 PRINT SPC(9) "Maximum ripple current in % = "DELX*KK
642 PRINT SPC(9) "DC input voltage :"
643 FOR J=1 TO 3
644 PRINT SPC(9) DVX(J)
645 NEXT J
648 KJ=KK+5
649 SCREEN 2
650 WINDOW (-3,-2)-(KJ,30)
660 LINE (0,0)-(KM,0)
670 LINE (0,30)-(0,0)
680 FOR M=1 TO 3
690 FOR J=1 TO KK
700 LINE -(X(J),Y(J,M)),,,&HAAAA
710 NEXT J
712 LINE (0,0)-(0,0)
715 NEXT M
720 FOR N=0 TO KK STEP 5
730 LINE (N,0)-(N,-.4)
740 NEXT N
750 FOR N=0 TO 28 STEP 2
760 LINE (0,N)-(-.2,N)
770 NEXT N
800 END
810 PRINT SPC(9) "DC input voltage :"
811 FOR J=1 TO 3
812 PRINT SPC(9) DVX(J)
813 NEXT J
-----------------------------------------------------------------------
```